Tertiary Climatic Evolution and the Development of Aridity in Australia

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The climatic record is deduced from palaeobotany and some other relevant studies. The record from southeastern Australia is the most comprehensive and is presented for comparison with other parts of Australia where there are few studies. In the southeast, the precipitation was well above the critical level for rainforest (1500 mm) during the Palaeogene. In the mid-late Miocene, precipitation declined to less than 1500 mm and in the late Pliocene-Pleistocene, there was a further decrease to about 500–800 mm. In the northeast of Australia, the precipitation remained well above the critical level for rainforest throughout the Tertiary and most of the Quaternary, hence this region is a refuge for many rainforest taxa. When the northwest of Australia is compared with the southeast, the climate of the former was drier than the latter throughout the late Tertiary and Quaternary.

Grasses were rare until the late Miocene when they show a steady increase which is maintained through the remainder of the Cainozoic. Grasslands developed first in the northwest and, presumably, Central Australia, but development was later in the southeast. A trend towards aridity started in the mid Miocene and continued through the late Tertiary. A degree of aridity was reached about the late Pliocene-early Pleistocene, but aridity has intensified during the Quaternary, especially in the latter part.

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INTRODUCTION

Weather and climate have a daily fascination. The extremes cause discomfort that lead some to claim 'the climate is changing'. While it is difficult to distinguish short term variation from a trend or change on the basis of these small scale observations, it is clear that climate has changed, and has changed drastically in the past: the Australian deserts once supported luxuriant vegetation.

This study reconstructs the Tertiary climate from the late Eocene, some 40 million years ago, when Antarctica was mostly ice free and Australia was almost entirely forested, and covers the crucial development of aridity. By the end of the Tertiary, some 2–3 million years ago, the climate resembled the modern status, but aridity has intensified, especially in the last half million years. The history of the vegetation is a major source of evidence of climatic change, but there are other studies which complement this history and add invaluable insights into past environments. These past changes suggest that the climate is likely to change in the future, and it could change dramatically from entirely natural causes.

The history of the vegetation is constructed from fossil evidence, mainly from palynology, and to a lesser extent, from macrofossils. Each source has both strengths and limitations. Pollen may be extracted from bore samples, hence palynology accesses sediment which may be hundreds of metres deep and the record from this source is comprehensive. Fossil leaves, the major source of macrofossil data, however, must be recovered from surface outcrops, although cuticles may be found in bore samples. Both pollen and leaves may show affinities with living taxa, but identification with a modern species is not always possible. Affinities are usually made with genera or families, but a fossil population may not coincide with any living taxon, even when natural affinities are evident.

Dust whipped up by wind may be blown out to sea and deposited in marine sediments. The dust fluxes in deep sea cores record the intensity of deflation on land (Glasby 1971; McTainsh 1989; Hesse 1994). Phytoliths, the silica bodies produced by grasses and many other plants, may form part of the dust flux and are another source of evidence. Palaeotemperatures deduced from oxygen isotope analyses of deep sea cores (Shackleton and Kennett 1975; Savin et al. 1975), corrected for continental ice volume where necessary (Feary et al. 1991; Isern et al. 1996), indicate surface sea temperatures and the trends may be extrapolated to the land. These records are independent of palaeobotany and hence are invaluable for confirmation of the record from palaeobotany, as well as filling in gaps in the record.

Reconstruction of the vegetation is achieved from the floristics of the palynofloras. The ecological tolerances and climatic limitations of present day taxa and vegetation are applied to the fossil assemblage to deduce past climates. Leaf physiognomic characters, such as dimensions, the nature of the margin, drip tips etc. are a direct expression of climate, irrespective of taxonomic affinities. The nature of the sediments also contains a climatic signal that is used as supplementary evidence.

Numerous experimental studies show that most of the pollen in an assemblage at any one site has been produced locally, within a radius of half a kilometre or less. A little pollen may have been transported in from long distances. (For reviews of the numerous studies on this subject, see Birks and Birks 1980, and Martin 1993.) The pollen assemblage is a reflection of the dominant type of vegetation and small, isolated patches of a different kind, such as may be found in sheltered gullies and gorges, may be palynologically invisible (Ladd 1979). Pollen in ocean cores, however, has been transported from land either by wind or runoff from rivers and studies of marine surface sediments show that the pollen in them is a general reflection of the regional vegetation on land (Mudie 1982; Turon 1984; Prell and van Campo 1986; Heusser 1988; Mudie and McCarthy 1994).

All kinds of plant parts require the anaerobic conditions of lakes, swamps, bogs etc. for preservation. The vegetation growing around these sites, which occupy the lowest part of the topography, are best represented in the fossil record. Plants growing on sites distant from the sedimentary basin, such as the hilltops or steep slopes usually have little chance of being fossilised.

The vegetation units identifiable in the fossil record are usually fairly broad and general. The units of vegetation used in this study are those in common usage and are defined thus:

Rainforests

Rainforests or closed forests (Specht 1970) are usually structurally and floristically complex. They are found in the better watered environments. *Eucalyptus* is not a normal part of rainforests. There are many different types of rainforest in tropical, subtropical and temperate regions. In Australia, tropical rainforests are best developed north of 21° latitude, although patches may extend further south. Subtropical rainforests are most common between 21° and 35° south and temperate rainforests are the dominant type south of 35° (Webb 1959), although small patches of the latter may be found as far north as 28°. *Nothofagus* is found in temperate rainforests which are especially well developed in Tasmania, New Zealand and Chile, extending to about 50–55°S (Riley and Young 1972). Rainforests may be divided into 'wet', with *Nothofagus*, and 'dry', usually with various gymnosperms (Kershaw et al. 1994). In drier locations, some scrubs and vine thickets are closely related floristically to rainforests and hence are included in this classification (Webb 1959; Webb and Tracey 1981).

Sclerophyll forests or open forests

Sclerophyll or open forests (Specht 1970) are most commonly dominated by *Eucalyptus* and/or *Casuarina/Allocasuarina*. Wet sclerophyll forests have rainforest or other mesic taxa in the understorey layers, and if left unburnt and undisturbed, may revert to rainforest (Ashton 1981). Dry sclerophyll forests do not have rainforest taxa. The understorey in these forests contains sclerophyllous shrubs (Gill 1981). Fire is an integral part of the environment of sclerophyll vegetation (Ashton 1981; Gill 1981).

Open vegetation

In forests, the tree canopy forms an almost continuous layer whereas in woodlands, the trees are well spaced. If there are few trees, the vegetation is more open and there is a well developed layer of shrubs, grasses and/or herbs. With a dense tree cover, insufficient light filters through the trees to support the ground layer (Specht 1970). In this study, open vegetation refers mainly to shrubland, grassland, and/or herbfield.

The sites studied for Tertiary palynology are shown in Fig. 1. Southeastern Australia has been studied most intensively but most of these studies present a disjointed sequence which must be pieced together for a coherent history. Dating is usually achieved by correlation with a dated sequence as most sediments cannot be dated directly and there is little independent evidence of the age. There are a few sites on the continental shelf and in the deep sea that yield pollen which must have come from the vegetation on land. These sites present a more continuous sequence that is well dated by independent evidence from marine foraminifera. Figure 1 shows that there are large areas for which there is no evidence.

This review presents the climatic evolution of southern Australia, which has a relatively good record, for comparison with northern Australia where the evidence is sparse.

SOUTHERN AUSTRALIA

The climate over most of southern Australia is temperate, becoming subtropical in the north and dry continental, semi-arid and arid in the central and inland regions (Foley 1954). Patches of rainforest are found along the east coast and in Tasmania but *Eucalyptus* forests and woodlands are dominant over most of the area. Open shrublands and grasslands are found in the semi-arid and arid regions.

Most of the evidence comes from southeastern Australia and this region covers Tasmania, Victoria, New South Wales and the southeast of South Australia. There are a few sites in central and southwest Australia.

Palaeovegetation

In southeastern Australia, the Lachlan River Valley on the western Slopes of the Great Dividing Range (H-F-C on Fig. 1) has an almost continuous record from late Eocene to the Pleistocene (Fig. 2). The vegetation was rainforest with abundant *Nothofagus* throughout the Oligocene, arguably the wettest period in the Tertiary. In the late Oligocene-early Miocene, *Nothofagus* declined, but the vegetation was still predominantly rainforest (Martin 1987).

The mid Miocene was a time of profound change when rainforests were decimated and myrtaceous forests became predominant. The carbonised particle or charcoal content is greater in the myrtaceous pollen assemblages than in the rainforest assemblages, showing that periodic burning had become part of the environment, thus inferring that the vegetation was sclerophyll forests and not rainforest, for the latter rarely burns. This indirect

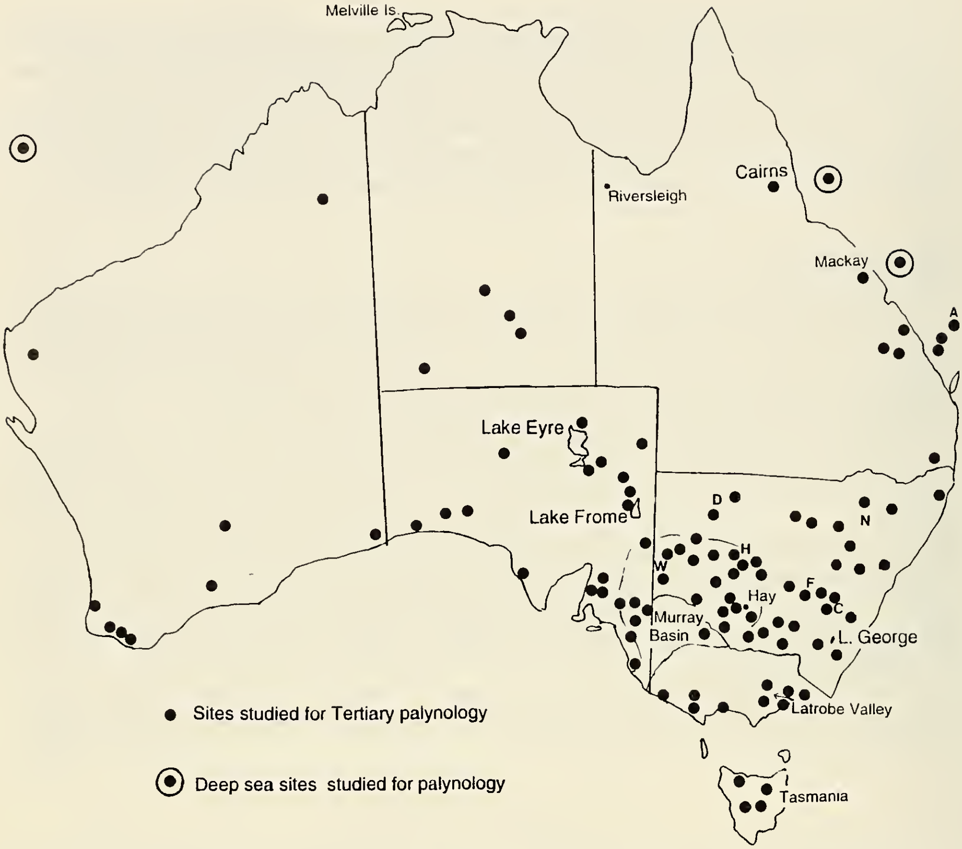

Figure 1. Sites studied for Tertiary palynology. The sites used for reconstructions in Fig. 2 are: H, Hillston; F, Forbes; C, Cowra, all of the Lachlan River Valley; A, the Aquarius well on the continental shelf; D, Darling River; N, Northern New South Wales; W, western region of southeastern Australia.

method of identifying eucalypt vegetation is necessary as *Eucalyptus* pollen is difficult to distinguish from other myrtaceous pollen types (Martin 1987). Some rainforest taxa are present in these myrtaceous assemblages, hence the interpretation of wet sclerophyll forests.

There is a hiatus of non deposition and/or erosion in the late Miocene, thought to correspond with the late Miocene low sea level (Fig. 2). In the late Miocene-early Pliocene, there is a brief resurgence of rainforest, followed by a return to wet sclerophyll forest. In the late Pliocene, the tree taxa declined and the vegetation became more open, viz, woodlands, grasslands and herbfields (Martin 1987).

When the records from other sites in southeastern Australia are compared with that of the Lachlan River Valley, the trends are generally similar but with some local differences. In Tasmania, the palynological record is limited (Kershaw et al. 1994), but there is a rich macrofossil record (Hill 1992; Carpenter et al. 1994). The Tertiary vegetation contained abundant rainforest taxa which persisted into the Quaternary when taxa common in modern sclerophyllous heathlands and woodlands became increasingly common. The late Quaternary vegetation was mainly *Eucalyptus*, Asteraceae and Poaceae, but *Nothofagus* and other rainforest taxa were still present as well. Thus rainforest has had a

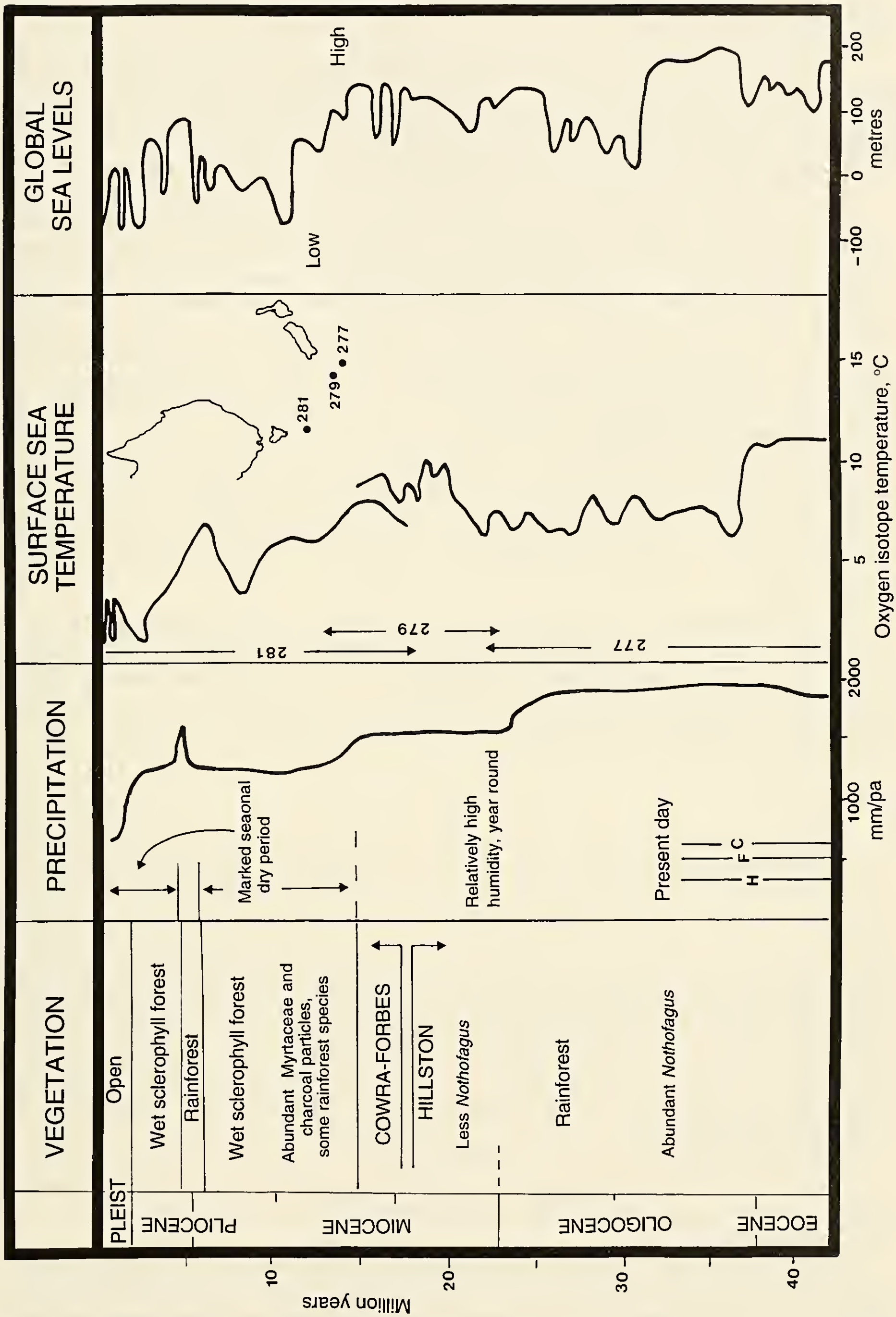

Figure 2. Reconstructions of the vegetation and climate from late Eocene into Pleistocene for the Lachlan River Valley, from Hillston to Cowra. See Fig. 1 for location. Present day levels of precipitation are for: H, Hillston; F, Forbes; C, Cowra. Oxygen isotope temperatures are from Shackleton and Kennett (1975) and global sea levels from Haq et al. (1987). Note: The surface sea temperatures are not corrected for continental ice volume (see text).

continuous presence through the Neogene and Quaternary in Tasmania (Carpenter et al. 1994; Kershaw et al. 1994).

The early–mid Miocene of the Latrobe Valley, southeast Victoria (Fig. 1) has abundant *Nothofagus* and other rainforest taxa. Casuarinaceae and sclerophyllous taxa are present as well. The rainforest taxa are also well represented in the late Miocene but have disappeared in the late Pliocene-early Pleistocene, when *Eucalyptus*, Asteraceae and Poaceae become abundant (Kershaw et al. 1994; Blackburn and Sluiter 1994).

In the Southern Highlands (Lake George and other sites in the region, Fig. 1), rainforest is well represented in the early-mid Miocene and extends into the late Pliocene, after which Asteraceae and Poaceae become prominent (Kershaw et al. 1994). In northern New South Wales (N on Fig. 1), rainforest is well represented in the mid-late Miocene. In the Pliocene, there is very little *Nothofagus* or 'wet' rainforest, but the gymnosperm taxa, and especially Araucariaceae ('dry' rainforest) are well represented. Asteraceae and Poaceae become abundant in the Pliocene-Pleistocene (Kershaw et al. 1994). The western region of southeast Australia (W on Fig. 1) shows similar patterns, with rainforest well represented in the late Oligocene to early-mid Miocene and diminishing in the Pliocene (Kershaw et al. 1994).

Late Oligocene–early Miocene assemblages along the Darling River, the most northwesterly part of southeastern Australia (D on Fig. 1), have a diverse rainforest flora, but in low frequencies and the vegetation was mainly sclerophyll, with some pockets of rainforest, probably along the river valleys, the habitats with the most favourable moisture relationships. Asteraceae and Poaceae become common in the Pliocene-Pleistocene (Martin 1997).

The sites studied from southwest Australia and southern coastal South Australia (Fig. 1) are mainly Eocene in age, with one Pliocene site. The Eocene palynofloras have abundant *Nothofagus* and other rainforest taxa (Macphail et al. 1994) and are generally similar to those in southeastern Australia. By the Pliocene, the vegetation had become sclerophyllous forests or woodlands dominated by Casuarinaceae or Myrtaceae (Bint 1981).

Palaeoclimate

The precipitation deduced from the climatic requirements of comparable present-day vegetation (see Martin 1987) is shown in Fig. 2. The early Oligocene was a time of very high precipitation, over 1800 mm, with high and constant humidities. Precipitation declined somewhat in the Oligocene, and in the early Miocene, it was probably closer to 1500 mm, the lower limit for widespread rainforest in New South Wales today. In the mid-late Miocene, precipitation decreased to 1000–1500 mm, the limits for wet sclerophyll, and there must have been a marked dry season to allow burning on a regular basis. In the late Miocene-early Pliocene, precipitation increased to over 1500 mm at the time of the rainforest revival. Subsequently, it decreased to below 1500 mm and in the late Pliocene-Pleistocene, to about 500–800 mm (Fig. 2). The present day levels of precipitation are shown on Fig. 2. for comparison, and they are less than those for the late Pliocene-early Pleistocene.

When the palaeovegetation of the other sites in southeastern Australia are compared with that of the Lachlan River Valley, they suggest that it was wetter in Tasmania and the southern highlands and drier in the northwest of the region, just as it is today (Martin 1986; 1990a).

Temperatures may be deduced from the palaeovegetation in a similar way to that of precipitation, but these two factors are not independent. When temperatures are higher, there is more evaporation and the climate is more humid. Once the climate becomes colder, it is also drier. The oxygen isotope record from deep sea cores (Shackleton and Kennett 1975) has been used to estimate surface sea temperature but it also indicates continental ice volume. In the Neogene and Quaternary, however, the record is influenced by both factors and corrections for ice volume are applied (Feary et al. 1991; Isern et al. 1996). Figure 2 presents the surface sea temperatures from Shackleton and Kennett (1975). Temperatures are high in the late Eocene, probably the highest for the Tertiary, decreasing in the Oligocene, when the Antarctic ice cap was developing, and increasing in the early-mid Miocene. Temperatures show a marked decline in the late Miocene, with a subsequent rise in the late Miocene-early Pliocene, followed by a sharp decline in the late Pliocene. Temperatures of the Pleistocene fluctuated with the glacial/interglacial cycles. The decline in temperatures through the Tertiary parallels the build up of ice on Antarctica (Kennett 1993).

Precipitation and temperatures (Fig. 2) are roughly parallel, especially from the Miocene on. Warmer times were also wetter and conversely, colder times are drier, as expected. In the Australian context, precipitation has been the overriding control, hence a clear, unambiguous temperature signal is not evident in the record from the palaeovegetation.

The precipitation record in Fig. 2 suggests that there are long periods of relative climatic stability and short periods of dramatic change. These periods of change coincide with some worldwide events which have a profound impact on climate. Global changes in sea levels (Haq et al. 1987) are also shown on Fig. 2. When sea levels are high, the continental shelves and low lying areas on land are flooded. These shallow seas warm up and evaporation is high, hence precipitation is increased. When sea levels are low, the continental shelves are exposed, the land is well-drained and the deep seas bordering the shelves are cold, hence evaporation and precipitation are both low.

The record of sea level, temperatures and precipitation show roughly similar trends from the Miocene on. There are high levels in the mid Miocene, low levels in the late Miocene, with another high in the early Pliocene. The peaks do not coincide exactly, for there may be an apparent lag due to some specific local factor or imprecise dating. The parallel trends do not hold as well in the latest Tertiary because the ice volume on Antarctica had become a significant factor. The temperature curve from Shackleton and Kennett (1975) was selected because it is the record closest to Australia (see Fig. 2) and hence has most relevance to southeastern Australia, but this curve is essentially similar to that of Savin et al. (1975) for the Atlantic and Indian Oceans, and reflects general global trends in climate.

In these global records of sea levels and oxygen isotope surface sea temperatures, the periods that stand out are as follows:

1. High sea levels and warmer surface sea temperatures in the mid Miocene and the late Miocene-early Pliocene.
2. Low sea levels and cooler temperatures in the mid-late Miocene and again in the late Pliocene-early Pleistocene. The Quaternary glacial/interglacial cycles commenced in this latter period. These two periods mark substantial decreases in both temperature and precipitation.

The times of marked change in the palaeobotanical record coincide with these global changes in sea level and temperatures. The periods of low sea levels and decreased temperatures, with accompanying lower precipitation, were devastating to the rainforest.

NORTHERN AUSTRALIA

The northern part of Australia is tropical and the coastal strip subequatorial (Foley 1954) and experiences summer monsoonal rains (Leeper 1970). Rainforest is found in patches along the north and east coast and is best developed in northeast Queensland, but overall, rainforest occupies only a relatively small area. Most of the region is covered with open forest, woodland and/or shrubland (Specht 1970).

Northeast Queensland

Deep sea sites off Cairns and Mackay respectively (Fig. 1) have good records of late Miocene-Pleistocene palynofloras. The vegetation on the land nearest both sites was predominantly araucarian rainforest and casuarinaceous forest (Martin and McMinn 1993). The casuarinaceous pollen could indicate either *Gymnostoma*, a rainforest taxon, or *Casuarina/Allocasuarina*, sclerophyllous taxa (Kershaw 1970). There is, however, a suite of other sclerophyllous taxa, hence there must have been some sclerophyll vegetation. There is some cyclical variation between the araucarian and casuarinaceous vegetation, but no marked change. The pattern of change seen in southeastern Australia is not evident here, and extensive rainforest continues into the Pleistocene, until 120,000 years ago when the araucarian rainforest declines (Kershaw et al. 1993). Today, the Cairns district is the wettest region of Australia, and it may be that in the Neogene, the rainfall was well above the lower limits for rainforest, such that fluctuations did not provoke the decline in rainforest seen elsewhere in Australia. These deep sea sites collect pollen principally from the coastal vegetation which would have been closest to the site, whether the sea level was high or low. In contrast, a site on land would register the migration of the vegetation zones as they moved in unison with sea levels (Martin and McMinn 1993).

A site on the Atherton Tablelands, inland from Cairns, is thought to be Pliocene-Pleistocene in age (Kershaw and Sluiter 1982). *Podocarpus, Nothofagus,* Casuarinaceae and Myrtaceae were at times prominent in the vegetation. *Eucalyptus* is not separated from rainforest Myrtaceae, and there is a wealth of low frequency rainforest taxa. Araucarians were minimal (Kershaw and Sluiter 1982). This assemblage from the tablelands reflects different vegetation to that on the coast, but it is essentially rainforest. The A.O.G. Aquarius No. 1 well on the continental shelf (A on Fig. 1), has a good Neogene sequence (Hekel 1972). Araucarians, Casuarinaceae and Myrtaceae were common in the vegetation, the latter in contrast to the deep sea sites where Myrtaceae is minimal. Rainforest was a considerable part of the vegetation here also.

Rainforest, and hence a relatively high precipitation, was maintained throughout the Neogene in northeast Australia when rainfall was decreasing over most of the continent. Environments favourable for rainforest have continued to the present day and the Cairns region is still the wettest part of Australia today (Leeper 1970) and has the most extensive tracts of rainforest.

Feary et al. (1991) have reconstructed the changes in palaeotemperatures using surface sea temperature derived from the Tertiary oxygen isotope record corrected for ice volume and the decreasing latitude with continental drift (Fig. 3). For the Great Barrier Reef, temperatures were subtropical in the Eocene, temperate in the Oligocene, subtropical in the Miocene, and finally becoming tropical in the Pliocene-Pleistocene when the Great Barrier Reef entered tropical latitudes (see Fig. 3) (Feary et al. 1991). On average, temperatures were above the minimum required for tropical reef growth (20°C) from the middle Miocene to Holocene, except for intervals in the late Miocene-early Pliocene, when the temperatures fell to between 18° and 20°C repeatedly (Isern et al. 1996)

Northwest Australia

There are three Tertiary palynological sites in northwest Australia (Fig. 1). The two on land are ?Eocene in age (Truswell and Harris 1982) and contain some rainforest taxa found in deposits of a similar age in southeastern Australia. There is also an almost continuous sequence from late Miocene to the Recent in a deep sea site, off Port Hedland. There, the pollen would have originated from the land to the south, from Port Hedland and southwards, as there is a north-south canyon down the edge of the shelf which acted as a funnel (Martin and McMinn 1994).

In the late Miocene the vegetation was casuarinaceous forests and there were no

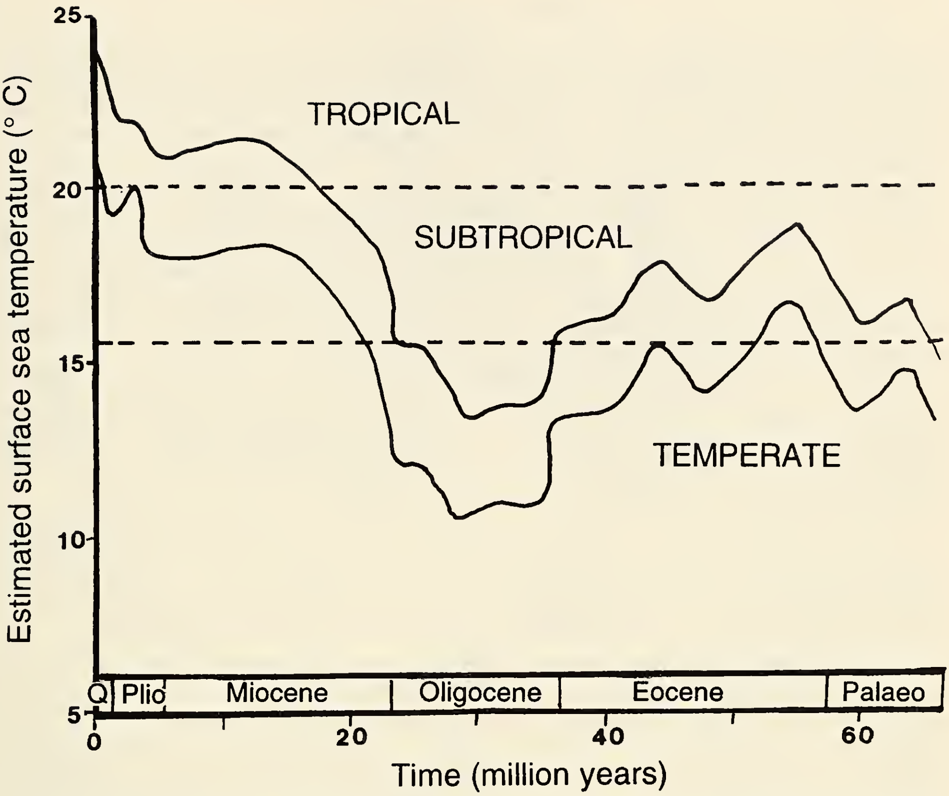

Figure 3. Inferred surface sea temperature for northeast Australia (from Feary et al. 1996). The upper curve represents the northern end of the Great Barrier Reef and the lower curve, the southern end. For further explanation, see text.

unequivocal rainforest taxa. The spores of ferns, bryophytes etc., indicative of damp habitats, are minimal, hence the climate was relatively dry. The casuarinaceous forests decline and are replaced by grasslands. *Acacia* is present with relatively high frequencies (for *Acacia*) which is always under-represented, suggesting that it was an important taxon in the vegetation. The chenopod type, pollen of Chenopodiaceae, is indicative of arid vegetation and increases in the Pliocene and Pleistocene. There is the minimal Myrtaceae pollen, hence minimal *Eucalyptus* and the lack of eucalypt dominated vegetation. The vegetation of the region today has large tracts where *Acacia* shrublands and hummock-tussock grasslands are dominant. This deep sea site probably reflects the development of the hummock-tussock grasslands (Martin and McMinn 1994; Specht 1970).

A remarkable macrofossil assemblage from Melville Island (Fig. 1) is, unfortunately, undatable. Cupressaceae, *Grevillea,* several other taxa of Proteaceae and *Melaleuca* indicate a non-rainforest community which probably had a seasonal climate (Pole and Bowman 1996).

When compared with southeastern Australia, the lack of rainforest and earlier increase in grasses suggests that it was drier in the northwest. Today, the northwest is much drier than the southeast, hence in general terms, climatic gradients in the Tertiary were parallel to those of today.

CENTRAL AUSTRALIA

Most of the sites in Central Australia, around Lake Eyre and in the Northern Territory are late Paleocene-late Eocene in age. The vegetation was mainly forests and herbaceous swamps. The rainforests were richly diverse in gymnosperms and there was some *Nothofagus,* but the latter was not as abundant as in coastal regions. There was a rich angiosperm flora also, and proteaceous taxa were prominent (Wopfner et al. 1974; Truswell and Harris 1982; Alley 1985; Sluiter 1991). Fossil leaf floras with small-sized leaves and an absence of drip-tips indicate some sclerophyllous vegetation (Greenwood et al. 1990, Christophel et al. 1992). Silicified moulds and casts of the fruits of *Eucalyptus; Angophora, Leptospermum, Melaleuca/Callistemon* and *Calothamnus* (Lange 1978) add to the sclerophyllous element. There was a mosaic with rainforest in the wetter habitats on the floodplains and along the watercourses with the sclerophyll vegetation on the drier and more nutrient deficient interfluves.

Palaeobotanical material younger than the late Eocene is rare in Central Australia. Once the climate became drier, the swamps etc, required for preservation, became scarce. When pollen is deposited in a swamp, it must be buried deep enough to escape the destructive effects of a fluctuating water table. The deep weathering, so common in inland Australia, has undoubtedly destroyed much of the palaeobotanical evidence.

A late Oligocene-early Miocene assemblage from Lake Frome contains rainforest gymnosperms, a little *Nothofagus* and abundant swamp taxa. Grass pollen is rare (Martin 1990b). (Extensive grasslands have been reported from this assemblage, the result of an incorrect identification. This topic is discussed further below.) At this time, Lake Frome was a freshwater lake with a wide, swampy border (Callan 1977), with rainforest in the hinterland.

A ?Miocene assemblage from the Ti Tree Basin, northwest of Alice Springs has abundant *Nothofagus*, swamp taxa and some grass pollen (discussed further, later) (Kemp 1978; Truswell and Harris 1982). An ?early-mid Miocene assemblage at Lake Hydra, near Lake Eyre, has minimal rainforest gymnosperms (araucarians and podocarps), the sclerophyllous Casuarinaceae and *Eucalyptus,* and abundant swamp taxa (Martin unpubl.). Thus there was more sclerophyllous vegetation and limited rainforest in Central Australia in the ?early-mid Miocene, when compared with southeastern Australia, and grasses were rare.

Evidence about the vegetation of the late Tertiary is very limited, but a few records exist. An ?early Pliocene assemblage at Lake Frome has abundant Casuarinaceae, rare *Eucalyptus* and a diversity of swamp taxa. There are no rainforest taxa present (Martin 1990b). The vegetation was thus entirely sclerophyllous. A ?late Pliocene-Pleistocene assemblage in the Lake Eyre Basin has low frequencies of Casuarinaceae and Myrtaceae, the only possible trees, and abundant Asteraceae (daisies), the chenopod type (saltbush-bluebush), Poaceae (grasses) and Cyperaceae (reeds). The vegetation was open shrublands (Martin unpubl.), not unlike the present day arid zone vegetation (Sluiter and Kershaw 1982).

The record in Central Australia shows the following progression when compared with southeastern Australia:

1. Late Paleocene-late Eocene: Varied rainforests were predominant and there were patches of sclerophyll vegetation. The climate was somewhat drier than that in the southeast.
2. Late Oligocene-mid Miocene: Sclerophyllous vegetation was well represented but rainforest was still present in the landscape, though much less than in southeast Australia where it was predominant. Swamp taxa were common.
3. ?Early Pliocene: Sclerophyllous vegetation predominated with little or no evidence of rainforest. Rainforest persisted in the more favourable habitats in the southeast.
4. ?Late Pliocene-Pleistocene: The vegetation had become open shrubland, with a significant herbaceous content and more like the arid vegetation of today. Forests were declining in the late Pliocene of the southeast.

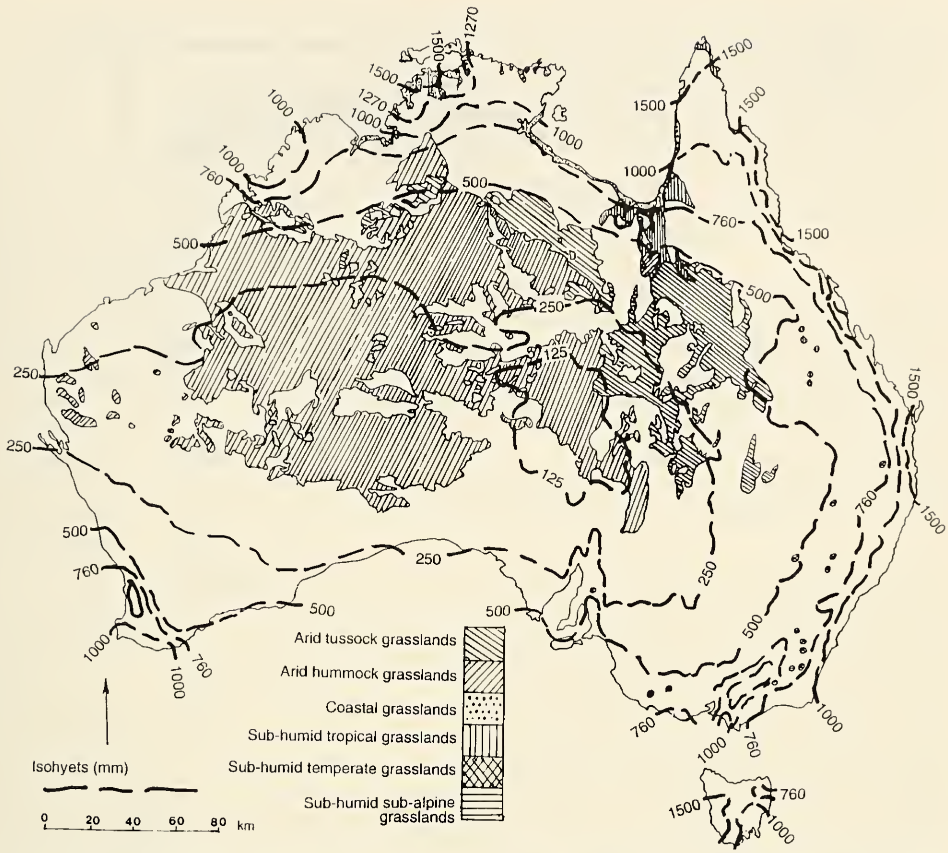

Figure 4. The distribution of grasslands in Australia and the annual precipitation. From Moore (1973) and Leeper (1970), respectively.

THE DEVELOPMENT OF GRASSLANDS

Today, grasslands predominate in arid and semi-arid regions of Australia (Moore 1973 and Fig. 4). The development of grasslands is of special interest, for without grasslands, there would be few, if any, grazing animals. The vertebrate palaeontological record shows that there were no grass-eating animals until the mid Miocene, when they were rare, and they did not become significant until the early Pliocene (Archer et al. 1989).

Grass pollen first appears in the fossil record in the Palaeocene (Muller 1981) but it is rare. Grasses and other small ground covering plants cannot flourish under a forest canopy because the forest floor is too shaded for good growth. An abundance of grasses may indicate grasslands, but there are many species of swamp grasses (Sainty and Jacobs 1981). Grasses may be abundant in salt marshes as well.

Most grasses are wind pollinated and are thus high pollen producers, contributing high frequencies to the pollen assemblage. Some grasses however, are cleistogamous, i.e. pollination takes place in closed flowers, hence pollen is not liberated in the air. The recognition of grasslands is based on the pollen assemblage as a whole, and not simply the frequency of Poaceae. If open vegetation has grasses of the type which do not contribute large quantities of pollen to the assemblage, then other herbaceous taxa, e.g. Asteraceae, are indicative of open vegetation.

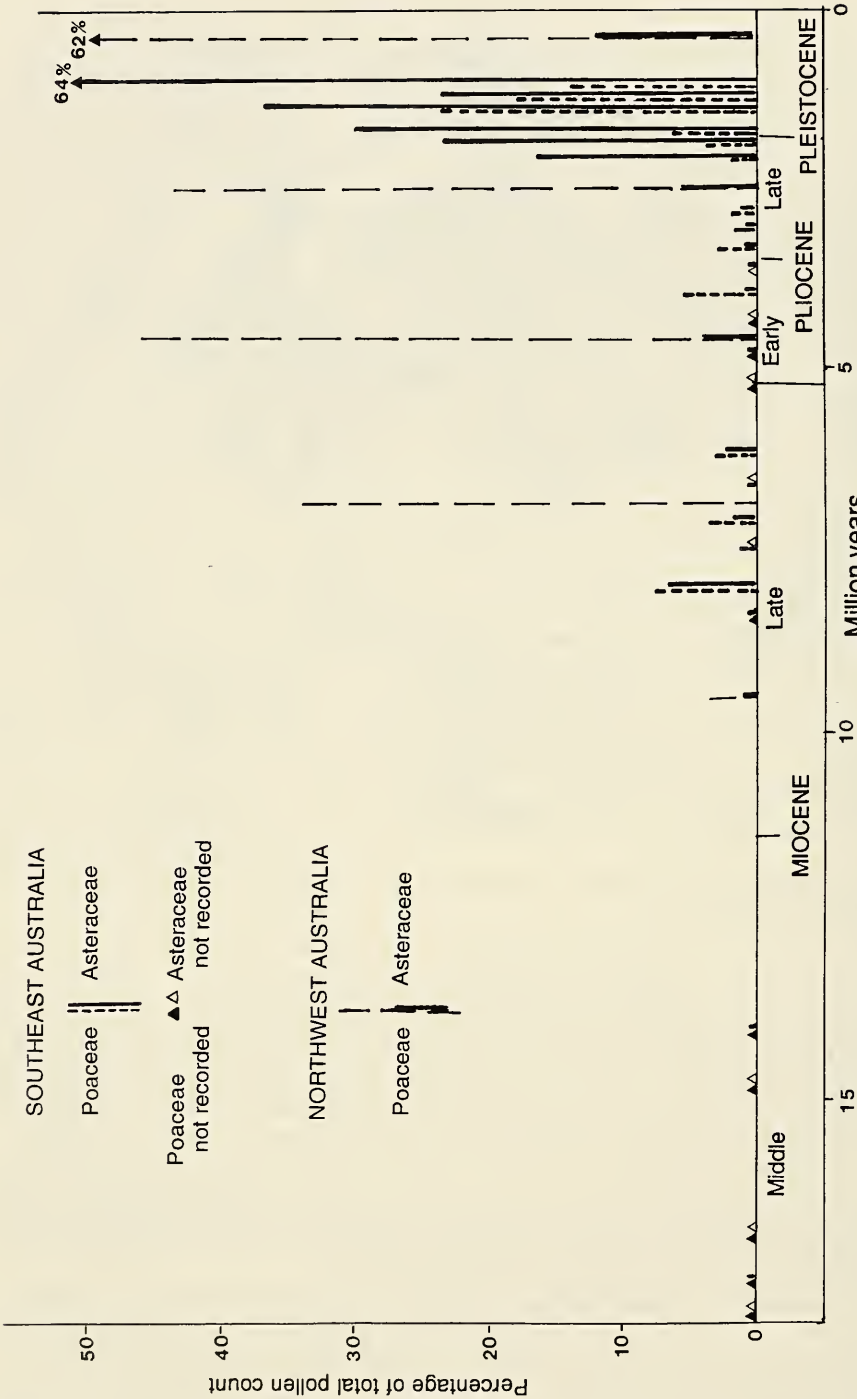

Figure 5. The increase in Poaceae and Asteraceae pollen during the Neogene for the Lachlan River Valley, southeastern Australia (from Martin 1969 and unpublished) and for the deep sea site off northwest Australia (from Martin and McMinn 1994). The place of each sample on the time scale is approximate.

Grass pollen is present in mid and late Eocene assemblages (Sluiter 1991; Martin unpubl.) but it is rare. In the late Oligocene-mid Miocene, grass pollen is present in low frequencies also, except for the Ti Tree Basin in Central Australia where 10% is reported (Kemp 1978; Truswell and Harris 1982). This assemblage contains a 'similarly high frequency of swamp taxa' (Truswell and Harris 1982, p. 72), hence the grasses may have been swamp dwellers. Moreover the assemblages are 'dominated by *Nothofagus brassii*' (Truswell and Harris 1982, p. 72), and such a dominance is not usually associated with grasslands. The report of these Ti Tree assemblages is very brief, and as such, is not a convincing case for grasslands. Further evidence from a full report of the assemblages is required before an interpretation of grasslands can be accepted.

The frequency of Poaceae and Asteraceae pollen in the assemblages from the Lachlan River Valley, used to reconstruct the vegetation and precipitation of southeastern Australia (Fig. 2) is shown in Fig. 5. The two taxa show similar trends, but Asteraceae becomes more abundant than Poaceae in the late Pliocene-Pleistocene. The marked increase in these taxa does not occur until the late Pliocene/Pleistocene (Fig. 5) and forms a recognizable horizon in southeastern Australia (Martin 1979). This horizon has been dated, using palaeomagnetic techniques, at 2.5–3 million years at Lake George (McEwen Mason 1989; 1991). This pattern contrasts with that of northwest Australia, where grass pollen increases from the late Miocene, through the Pliocene and into the Pleistocene, as shown on Fig. 5.

Grasses and many other plants produce phytoliths or opaline silica bodies in their cells. The size of the phytoliths is commonly below 30 m but they may be much larger. Small phytoliths may be transported by dust storms and deposited in marine sediments. Locker and Martini (1986) recovered phytoliths from Neogene sediments on the Lord Howe Rise. These authors assume that most of the phytoliths originated from grasses. Given that grasses are common in the semi-arid regions that suffer deflation, this assumption seems reasonable. Phytoliths may be found in wood, but the semi-arid source area of the dust was not largely forested. Cyperaceae and Restionaceae have phytoliths also and they may be abundant in swamps, but dust storms do not start in swamps. Figure 6 presents the frequencies of phytoliths in the deep sea site, more than 1,000 km from the coast (Locker and Martini 1986). Phytoliths first appear in the mid Miocene, are relative low throughout the Miocene, and increase in the early Pliocene. The pattern here is similar to that of grass pollen in the northwest deep-sea site (Fig. 5), and differs from the grass/daisy pollen frequency pattern in southeastern Australia (Fig. 5), where a substantial increase does not occur until the late Pliocene-Pleistocene. This evidence suggests that grasslands may have been present in Central Australia in the Pliocene, in regions for which there are no palaeobotanical records, for it is unlikely that the only source of the phytoliths was the northwest of Australia.

Extensive grasslands in the early Miocene were reported from Central Australia, on the evidence of abundant grass pollen (Callan and Tedford 1976). This report of early Miocene grasslands has been cited many times, e.g., Martin (1978, 1981, 1986), Kemp (1978), Truswell and Harris (1982) and Frakes et al. (1987). Re-examination of the original slides however, has shown that the abundant grass pollen is, in fact, Restionaceae, a swamp plant (Martin 1990b) and grass pollen is rare. There is an abundance of algae in the same sample, hence reinforcing the interpretation of extensive swamps and not extensive grasslands. There is thus no evidence of early Miocene grasslands.

THE DEVELOPMENT OF ARIDITY

The trend to a drier climate started in the Miocene, intensified in the Pliocene, with arid conditions approaching those of today being reached in the Plio-Pleistocene. This evidence for the development of aridity is very limited, given the prerequisites of lakes,

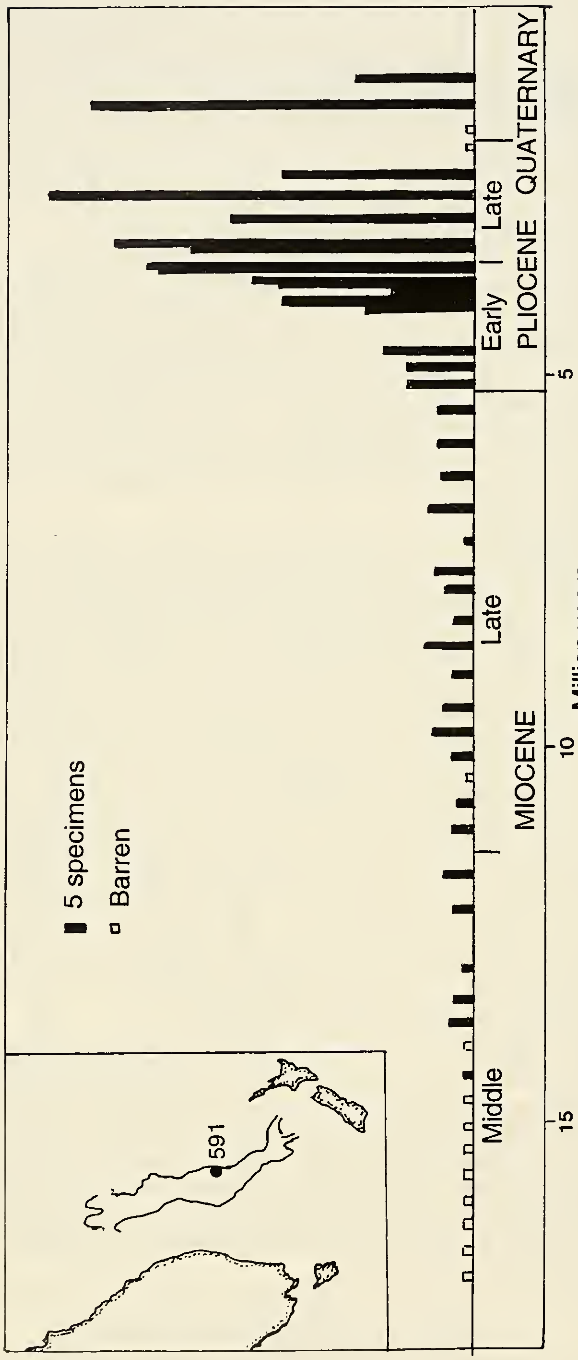

Figure 6. The frequency distribution of phytoliths originating mainly from grasses (see text) found in a deep sea site on the Lord Howe Rise. From Locker and Martini (1986).

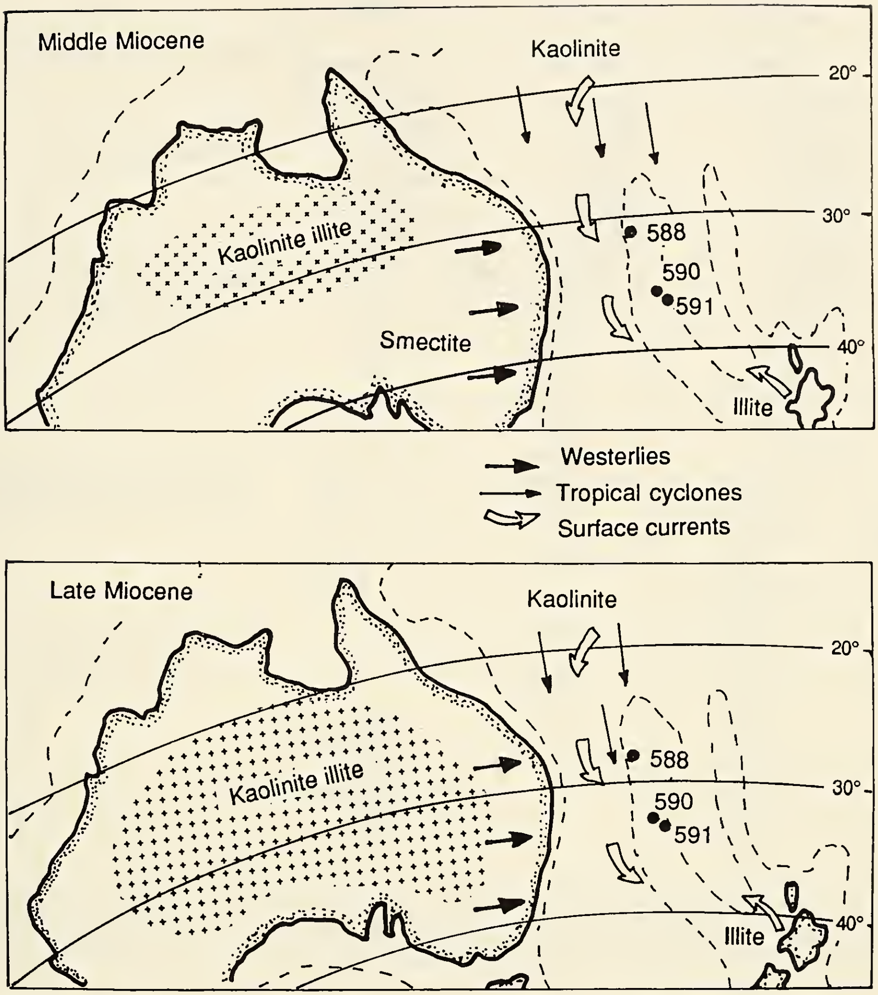

Figure 7. The expansion of aridification southwards in the Miocene, as interpreted from the S/I ratios of clay mineral assemblages on the Lord Howe Rise. From Stein and Robert (1986).

swamps etc. for pollen preservation, the few sites in arid/semi-arid regions that have been studied probably only record the wettest periods of the time (see the sea level curve in Fig. 2) and the wettest habitats. There is however, substantial evidence about the development of aridity from other studies, and the most pertinent of these are reviewed.

Windblown dust settling in the ocean is a source of evidence about deflation from the source area. Several deep sea sites on the Lord Howe Rise (Fig. 7) record Tertiary dust particles transported by westerly winds from Australia (Stein and Robert 1986; McTainsh 1989). These sites may collect terrigenous particles carried by ocean currents, or by winds from New Zealand. Volcanism is another source of dust. Today, the aeolian sediment influx is dominated by westerly winds bringing dust from the Australian deserts and semi-deserts, and all the evidence suggests that this was the case throughout the Neogene (Stein and Robert 1986).

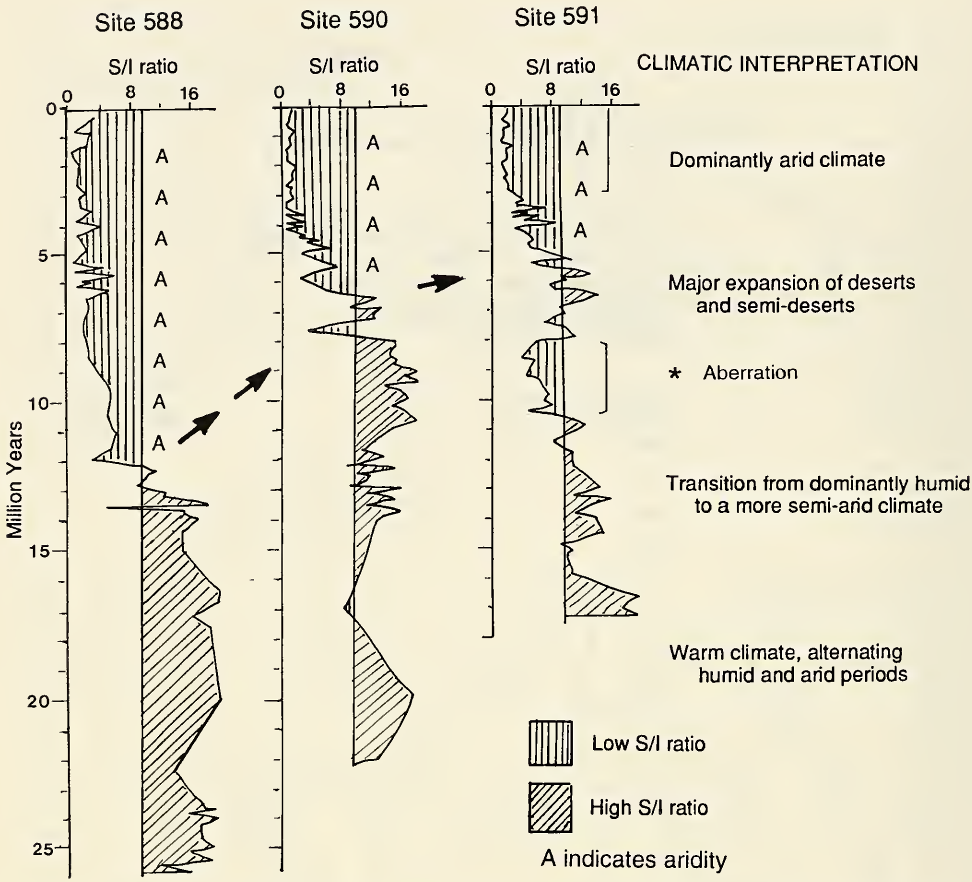

Figure 8. The smectite/illite (S/I) ratios of clay mineral assemblages in deep sea sites on the Lord Howe Rise. Black arrows mark the change from predominantly high to extremely low S/I ratios and indicate the beginning of aridification. *This aberration in Site 591 is thought to have originated from volcanic activity in New Zealand. From Stein and Robert (1986). For location of the sites, see Fig. 7.

Once the climate becomes drier and the vegetation is disturbed, wind erosion increases. The dust eroded from sand and stone deserts is less than that from semi-arid regions, but it is greater than that from humid regions. The size of the particles gives an indication of wind speeds. Different types of clay minerals may be used as palaeoclimatic indicators also. Illite is formed from predominantly physical weathering. Kaolinite is formed from chemical weathering in tropical areas. Kaolin rich soils in the arid regions of Australia were formed in more humid climates. Smectite is formed in humid to semi-arid climates. Today the snowfields in southeastern Australia collect mainly illite and kaolinite from the arid regions to the west. Dust of volcanic origin is identifiable (Stein and Robert 1986).

Figure 8 presents the smectite/illite (S/I) ratios for three deep sea sites on the Lord Howe Rise (from Stein and Robert 1986). Low ratios indicate aridity, as shown by ‘A’ on Fig. 6. In the latest Oligocene, the climate of the source areas was warm with alternating periods of humidity and semi-aridity. In the mid Miocene, the decrease in the S/I ratios at Site 588 suggest increased aridification in the northern to central parts of the continent. Southern Australia may still have been dominated by alternating humid and semi-arid climatic conditions. The decrease in the S/I ratios in the late Miocene at Site 590 is interpreted as an expansion of aridification southwards as shown in Fig. 7 (Stein and Robert 1986). This late Miocene southwards extension of aridification coincides with the late Miocene low sea level and the palaeobotanical evidence for a drier climate. The evidence from clay mineralogy suggests that aridification started in the north of the continent and expanded southwards (Fig. 7).

Lake Frome is now a dry salt lake, but in the early Miocene it was a large freshwater lake with a wide swampy margin. A study of the clay mineralogy shows that in the early Miocene, the climate was sub tropical. There was a trend towards aridity from the mid Miocene. Marked climatic fluctuations, which may have been seasonal, were superimposed on this overall trend. The climate approached the present Mediterranean type in the medial Pleistocene (Callan and Tedford 1976; Callan 1977). These interpretations for Lake Frome are in accord with the hypothesis of Stein and Robert (1986) for the southern part of the continent.

The sediments of Lake George in southeastern Australia (Bowler 1982) have been palaeomagnetically dated to the last 2.5 million years. Initially, Lake George shows continuous deposition of laminated clays representing widespread humid and equitable conditions over its region. About 5–6 million years ago, there was a drastic change: the lake dried out and the sediments became deeply weathered. It is thought that this change occurred at the time of the late Miocene low sea level. The climate was seasonally arid to allow the lake to dry out, but with summer rainfall sufficient to promote the deep weathering. High lake levels returned briefly at 2.5 million years ago and from this time on, the lake levels oscillated between lake-full and lake-dry conditions. This pattern continues to the present, with amplifications in the last 0.7 million years. These oscillations heralded the onset of the cooler temperatures of the Pleistocene and the glacial/interglacial cycles (Bowler 1976, 1982).

From these studies of Lake George and elsewhere, Bowler (1982) advocates that aridity developed from the south. It appears that Bowler's hypothesis contradicts that of Stein and Robert (1986) who postulate that aridification developed first in the north and expanded southwards (see Fig. 7). The two hypotheses, however, apply to different times. The hypothesis proposed by Stein and Robert is based on evidence for the mid-late Miocene, from 14–15 to 5–6 million years ago (Fig. 8), whereas Bowler's hypothesis relies on evidence for the period >6–2.5 million years to the present. The early stages of aridification may have been strongly seasonal (Callan 1977) and a well-marked dry season would be sufficient to generate the dust storms necessary to transport dust out to sea, even if there was a wet season as well. The S/I ratios (Fig. 8) suggest that aridity intensified about 3 million years ago, and this part of Stein and Robert's evidence is in accord with Bowler's evidence from Lake George.

Another hypothesis places the beginnings of aridity in the Eocene and uses evidence that the change from terrigenous to carbonate sedimentation off the western margin of the continent infers cessation of efficient drainage from the land (Quilty 1982). The lack of terrigenous sediment, however, only infers minimal erosion from a flat, well-vegetated landscape. There is contradictory evidence to refute this hypothesis. Laterite formation requires a warm, wet climate and there is more than one episode of lateritisation. Palaeomagnetic dating suggests that the dominant period of laterite weathering over a large part of Australia was late Oligocene to early Miocene (Idnurm and Senior 1978; Schmidt et al. 1976). Moreover, river systems in the arid region of Western Australia have been inactive only since the mid Miocene (van der Graff et al. 1977). This latter evidence suggests that the trend towards aridity did not start until the mid Miocene on the western margin of the continent.

Beard (1977) presents a hypothesis that aridity started in the northwest of the continent in the mid Eocene, some 45 million years ago, on the basis that this part of Australia was the first to reach the dry anticyclone belt by continental drift, i.e., it drifted into aridity. The evidence presented above does not support this hypothesis. Kennett (1993) considers that continental drift alone is too slow to account for the climatic changes observed .

In a study of foraminifera and sedimentation off northwest Australia, Apthorpe (1988) concludes that the region was a warm water to tropical province throughout most of the Cainozoic. The evidence suggests that there were dry periods and perhaps seasonally dry climates at times during the late Palaeocene and late Eocene, but not the beginning of the aridity seen today. The undated palaeobotanical evidence from Melville Island (Pole and Bowman 1996) also suggests a seasonal climate.

Aridification intensified with the Quaternary period which is dominated by the glacial/interglacial cycles. The glacial periods were colder, windier and more arid (see Kershaw 1981; Kershaw et al. 1991; Dodson 1992, 1994; Hope 1994). Desert dunes were more mobile (Wasson 1989), the arid zone expanded in size (Dodson and Wright 1989) and the dust flux in marine sediments increased (Hesse 1994). About half a million years ago, there was a further increase in aridity to that resembling today (Bowler 1982). Palaeobotanical records only exist for the latter part of the Quaternary. In southeastern Australia, the vegetation was predominantly open shrubland/grassland/herbfield during glacial times and forested in the interglacial periods (Dodson 1992; Hope 1994). In northeast Queensland, sclerophyll vegetation was dominant in the glacial cycles and rainforest in the interglacials (Kershaw 1985, 1994). In the last glacial period, the Gulf of Carpentaria was exposed and a savannah-like environment prevailed. The runoff/evaporation rates were about half of the present ratio (Torgersen et al. 1988). In northwest Australia, the last glacial period was distinctly drier and grasslands replaced the eucalypt forest of the previous interglacial (van der Kaars 1990). It is beyond the scope of this study to deal with the Quaternary in detail, but the constantly changing environment, on a scale of thousands of years, must have had a profound influence on the biota.

The extensive Tertiary vertebrate faunas of Riversleigh (Archer et al. 1989, 1994) carry a climatic signal but there are few palaeobotanical records anywhere near Riversleigh (Fig. 1) and extrapolation from the few records in the northwest and northeast must be done with great caution. Only the late Quaternary study, covering the last 35,000 years from the Gulf of Carpentaria (Torgersen et al. 1988) is geographically close to Riversleigh. Today, Riversleigh experiences a monsoonal climate and while the mechanics of the present day monsoonal system is well researched, very little is known about its history (Crisp 1996). There is some evidence of seasonal climates in the early Tertiary from both northern (Apthorpe 1988; Pole and Bowman 1996) and Central Australia (Callan and Tedford 1978; Greenwood 1996), but it is not known if it was monsoonal.

CONCLUSIONS

In southeastern Australia, there are two periods of dramatic change, one in the mid Miocene, when widespread rainforest disappeared and sclerophyllous forests became dominant, and the other in the late Pliocene-Pleistocene, when the forests declined and open vegetation became dominant.

The Tertiary precipitation curve shows long periods of relative stability and short periods of marked change. Other parts of the world show marked climatic change about the same time. These times of change may be correlated with global changes in sea levels and climate.

When all the sites in southeastern Australia are compared, they indicate that it was wetter in Tasmania and on the southern highlands, and drier inland and to the northwest, i.e., during the Tertiary, there was a climatic gradient parallel to that of today.

Northeast Queensland shows relative stability of the rainforest/sclerophyll vegetation from the late Miocene through most of the Pleistocene, when compared with southeastern Australia. The precipitation was maintained above the limits for rainforest throughout the period, hence northeast Queensland became a refuge for taxa which could not tolerate the drying environment elsewhere.

Northwest Australia shows a progression from casuarinaceous forests to shrublands/grasslands through the late Miocene-Pleistocene, very different to that of the southeast which still had appreciable rainforest.

The Eocene of Central Australia had both rainforest and sclerophyllous vegetation, and the climate was seasonal. Rainforest decreases earlier in Central Australia than in southeastern Australia.

When the vegetation and climate of all these different parts of Australia are compared, they suggest that a general climatic gradient parallel to that of today, existed throughout the Tertiary.

Grasses were rare in the early Tertiary and started increasing in the late Miocene. Grasses increase in the Pliocene of central regions of Australia, and in the late Pliocene–Pleistocene of southeastern Australia.

The trend towards aridity is first detected in the mid Miocene. The late Pliocene-Pleistocene witnessed a marked increase in aridification and the present day level of aridity was reached about a half million years ago.

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